Distributed Signal Processing for Binaural Hearing Aids

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Outline

Outline

Hearing aids through the ages

Motivations

State of the art technology

BTE

ITE

ITC

CIC

- Analog vs. digital
- 2-3 (omni) directional microphones, 1 loudspeaker
- Main goal: improve speech intelligibility
- Tasks: compression, noise reduction, feedback cancelation

Problems

- Few closely spaced microphones
- Monaural/bilateral amplification

Solution: binaural hearing aids

Motivations

Challenges: stringent constraints of communication link

- Power: battery operated (1 Volt, lifetime 5-7 days)
- Delay: 5 ms to 15 ms (open/closed fitting)
- Rate: few bps to hundreds of kbps

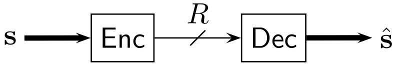
State of the art

- Large literature on multi-microphone systems (e.g., [JohnsonD93,VanTrees02])
- Rate-constrained nature of the link is not addressed

Outline

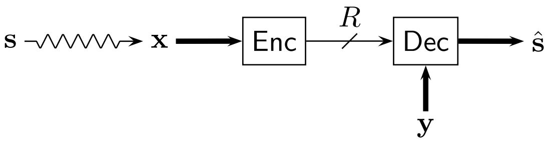
Information-theoretic Results

Source coding [Shannon59]

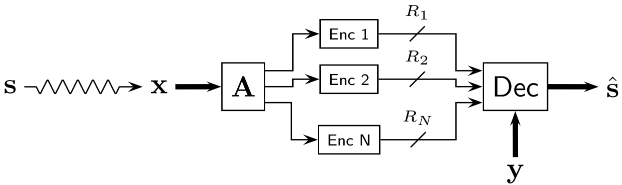


- Given: a source and a distortion criterion $d(s, \hat{s})$
- Assumptions: known distribution, unbounded coding delay and complexity
- Result: the rate-distortion function $R(D)$

Remote source coding with side information at the decoder [YamamotoI80]



Gaussian vectors and MSE distortion [RoyV08]



Transform coding: estimation stage followed by coding stage

[RoyV08] O. Roy and M. Vetterli, "Dimensionality Reduction for Distributed Estimation in the Infinite Dimensional Regime", IEEE Transactions on Information Theory, Vol. 54, Nr. 2, pp. 1655-1669, 2008.

Gaussian vectors and MSE distortion

Theorem

Optimal encoding strategy

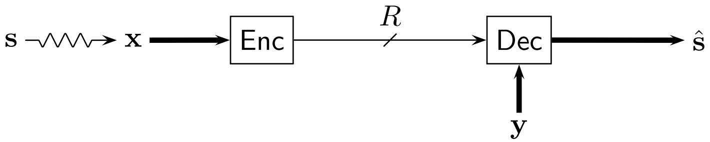
1. *Apply local transform* $\mathbf{A} = \mathbf{U}^H \mathbf{R}_{s\bar{x}} \mathbf{R}_{\bar{x}}^{-1}$, *where*

$$\bar{\mathbf{x}} = \mathbf{x} - \mathbf{R}_{xy} \mathbf{R}_y^{-1} \mathbf{y}$$
$$\mathbf{U}^H \mathbf{R}_{s\bar{x}} \mathbf{R}_{\bar{x}}^{-1} \mathbf{R}_{s\bar{x}}^H \mathbf{U} = \mathit{diag}\,(\lambda_1, \ldots, \lambda_N)\ .$$

2. *Reverse "water-filling" on* $\lambda_1, \ldots, \lambda_N$
3. *Conditionally independent scalar Wyner-Ziv coding*

Coding strategies

- Side information aware (SIA)



Information-theoretic Results

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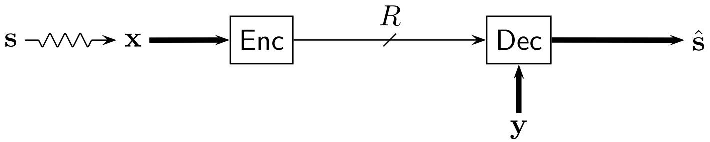

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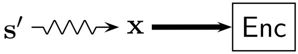

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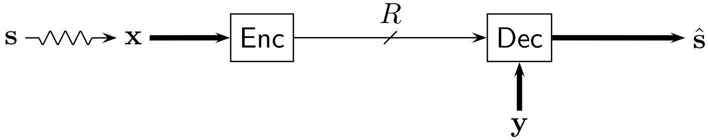

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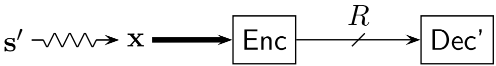

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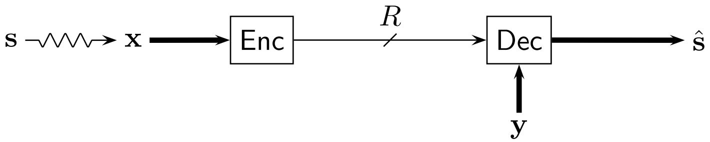

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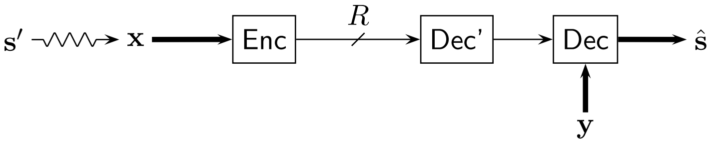

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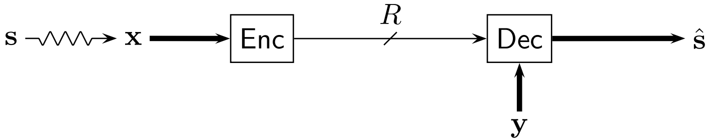

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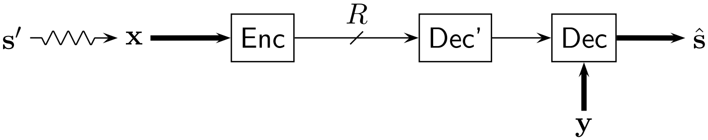
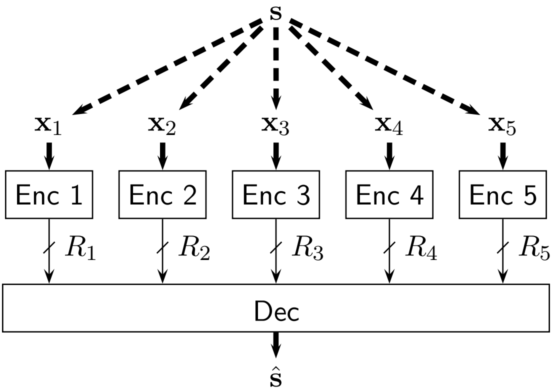


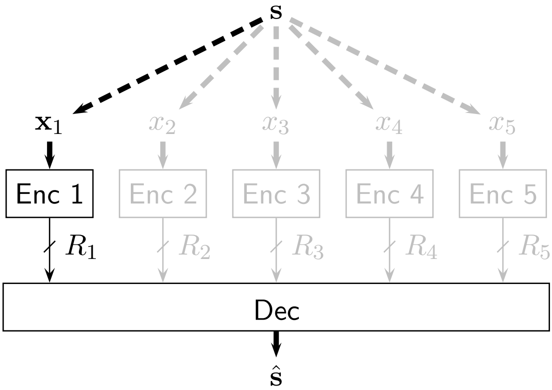
Sub-optimality of SIU coding: estimation stage and coding stage

Information-theoretic Results

Application: locally optimal distributed estimation [RoyV08]



Application: locally optimal distributed estimation [RoyV08]



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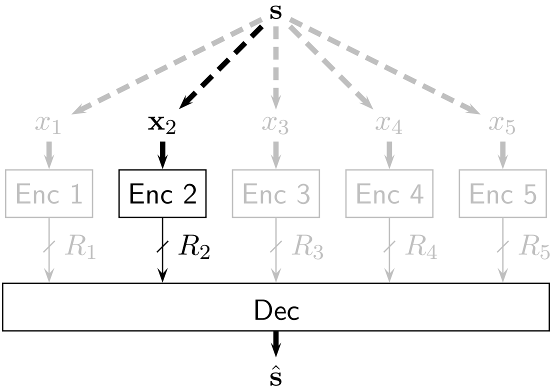

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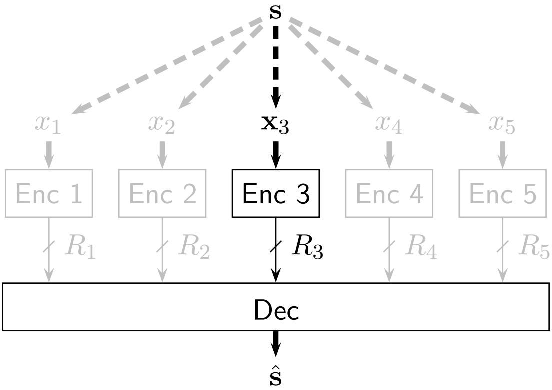

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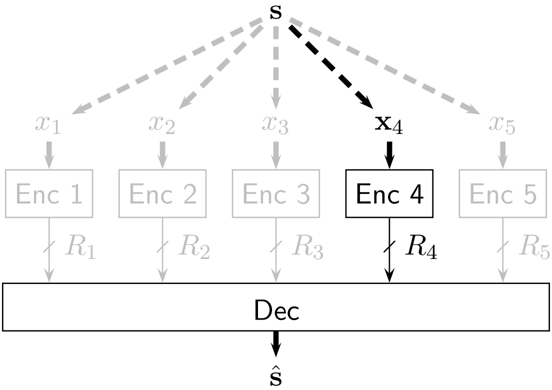

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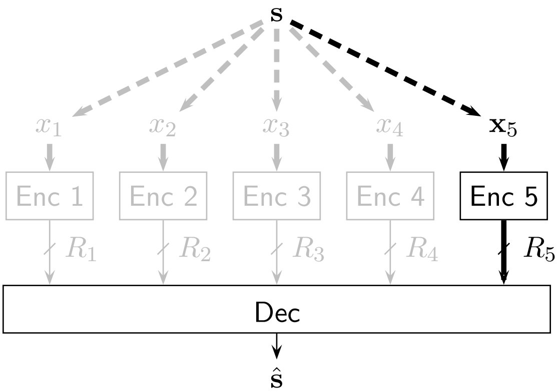
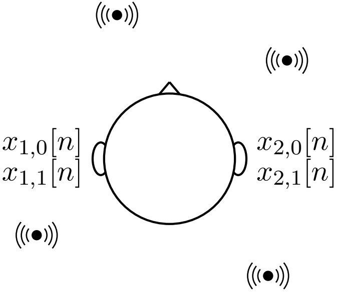


Outline

Binaural Noise Reduction

Recording setup



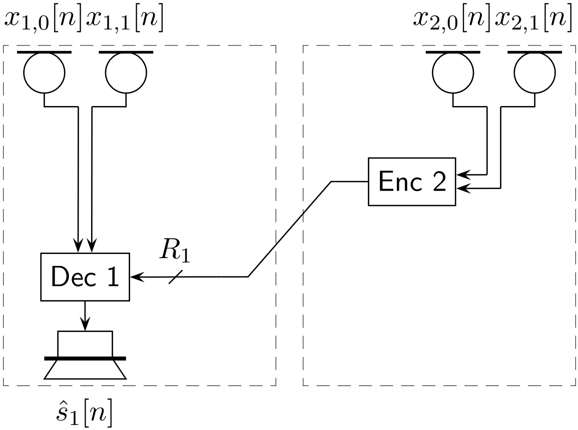
Recorded signals

$$x_{l,k}[n] = x^s_{l,k}[n] + x^n_{l,k}[n] \quad \text{for } l = 1, 2 \text{ and } k = 0, 1$$

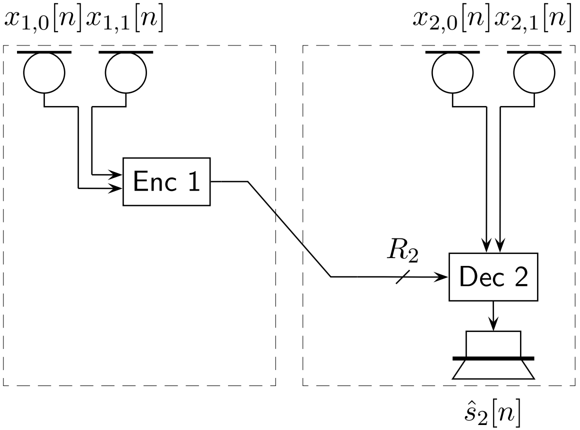
Desired (or remote) signals

$$s_l[n] = x^s_{l,0}[n] \quad \text{for } l = 1, 2$$

Monaural perspective: $D_1(R_1)$

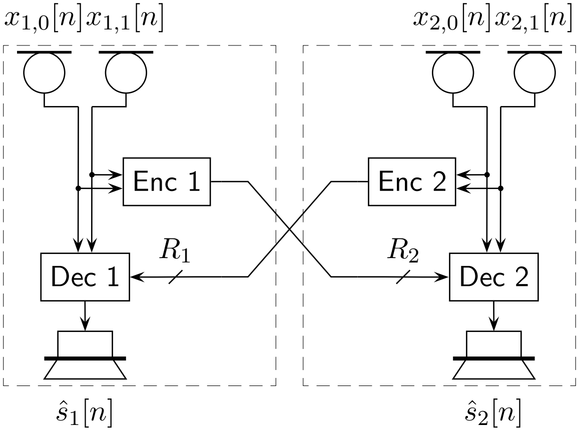


Monaural perspective: $D_2(R_2)$



Binaural Noise Reduction

Binaural perspective: $D(R)$ with $D = D_1 + D_2$, $R = R_1 + R_2$



Outline

Gain-rate Optimality

Gain-rate trade-offs [RoyV08b]

- Monaural

$$G_l(R_l) = \frac{D_l(0)}{D_l(R_l)} \quad \text{for } l = 1, 2$$

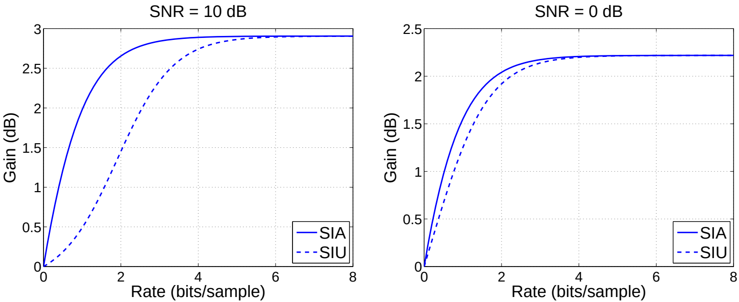
- Binaural

$$G(R) = \frac{D(0)}{D(R)}$$

[RoyV08b] O. Roy and M. Vetterli, "Rate-Constrained Collaborative Noise Reduction for Wireless Hearing Aids", to appear in IEEE Transactions on Signal Processing, 2008.

Gain-rate Optimality

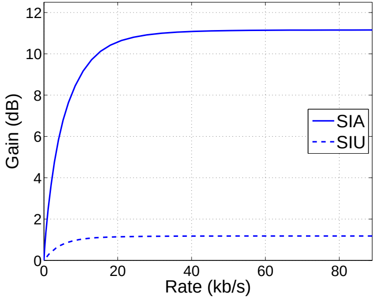
Monaural gain-rate trade-offs
(1 speech source, uncorrelated noise)

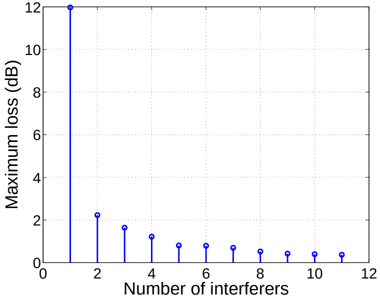


- Estimation stage: no loss
- Coding stage: higher the SNR, bigger the loss

Gain-rate Optimality

Monaural gain-rate trade-offs and maximum loss of SIU over SIA (1 speech source, one interferer, SNR $= 0$ dB)

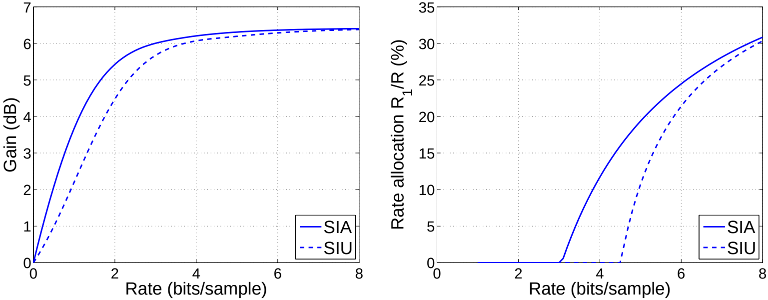




- Estimation stage: higher the noise correlation, bigger the loss
- Coding stage: higher the SNR, bigger the loss

Gain-rate Optimality

Binaural gain-rate trade-offs and rate allocation
(1 speech source, uncorrelated noise, $\text{SNR}_1 = 10$ dB, $\text{SNR}_2 = 0$ dB)



- The larger the SNR difference, the larger the rate threshold
- Rate threshold with SIU coding larger than with SIA coding

Outline

Distributed Source Coding of Binaural Innovation

Binaural innovation: two parametric models

- Based on binaural cues
- Based on sparse filter

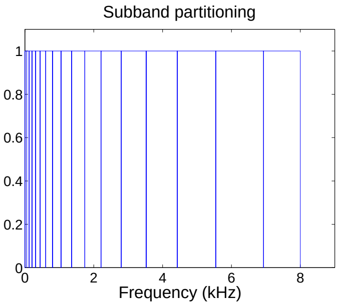
Applications

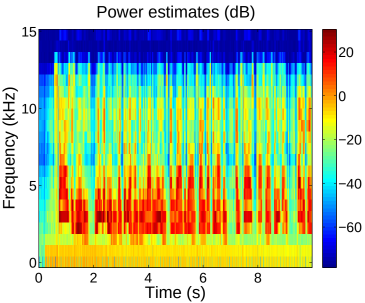
- Scene analysis
- Voice activity detection
- Distributed spatial audio coding

Distributed Source Coding of Binaural Innovation

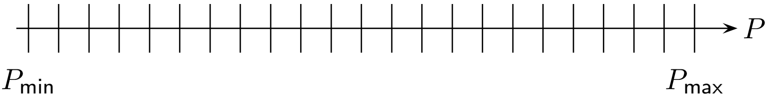
Model based on binaural cues

- Inter-channel level difference (ICLD): $P_1 - P_2$
- Inter-channel time difference (ICTD): $\tau_1 - \tau_2$
- Time-frequency processing





- Distributed coding of ICLDs [RoyV07]



[RoyV07] O. Roy and M. Vetterli, "Distributed Spatial Audio Coding in Wireless Hearing Aids", IEEE Workshop on Applications of Signal Processing to Audio and Acoustics, pp. 227-230, 2007.

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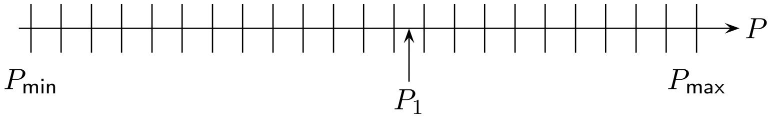

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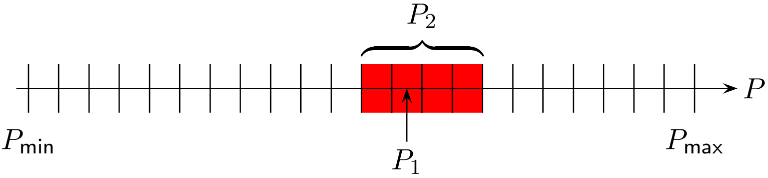

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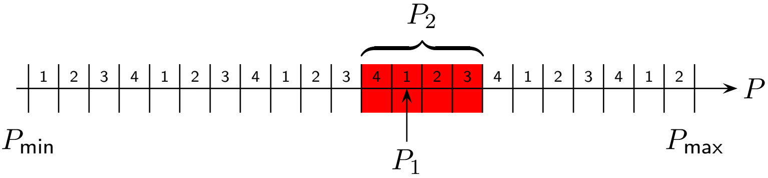

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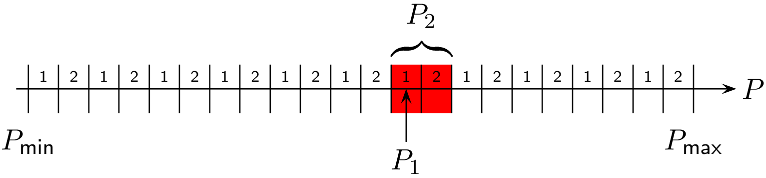
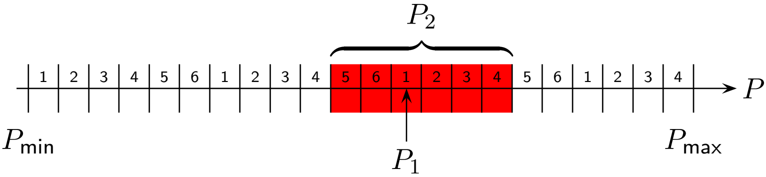


Low frequencies



High frequencies

Distributed Source Coding of Binaural Innovation

- Distributed coding of ICTDs [RoyV07]
  - Lookup table
  - No increase in bitrate
  - Low computational complexity
  - Satisfactory only to some extent

Distributed Source Coding of Binaural Innovation

Model based on a sparse filter

- Time-domain formulation $(0 \leq n < N,\ K \ll N)$

$$x_2[n] = h[n] \circledast x_1[n], \quad \text{where} \quad h[n] = \sum_{k=1}^{K} c_k \, \delta[n - n_k]$$

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- Frequency-domain formulation ($0 \leq m < N$, $K \ll N$)

$$X_2[m] = H[m] \odot X_1[m], \quad \text{where} \quad H[m] = \sum_{k=1}^{K} c_k \, e^{-j \frac{2\pi}{N} n_k m}$$

Distributed Source Coding of Binaural Innovation

Distributed sensing algorithm [RoyHLV09]

1. Hearing aid 2 computes DFT coefficients $X_2[0], \ldots, X_2[K]$

[RoyHLV09] O. Roy, A. Hormati, Y. Lu, and M. Vetterli, "Distributed Sensing of Signals Linked by Sparse Filtering", submitted to IEEE International Conference on Acoustics, Speech, and Signal Processing, 2009.

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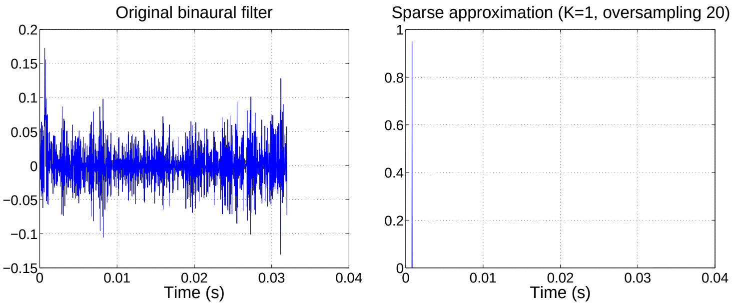
4. Hearing aid 1 computes DFT coefficients $H[0], \ldots, H[K]$
5. Hearing aid 1 recovers $H[m]$ for $0 \leq m < N$ using annihilating filter method

- Robustness to model mismatch: Cadzow's denoising [Cadzow88]



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- Locally optimal algorithm for distributed estimation
- Gain-rate analysis
  (closed-form formulas, optimal rate allocation)
- Method for distributed coding of binaural cues
- Distributed sensing scheme based on annihilating filters
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Thanks for your attention

Publications

RoyHLV09 O. Roy, A. Hormati, Y. Lu, and M. Vetterli, "Distributed Sensing of Signals Linked by Sparse Filtering", submitted to IEEE International Conference on Acoustics, Speech, and Signal Processing, 2009.

RoyAKV09 O. Roy, T. Ajdler, R. L. Konsbruck, and M. Vetterli, "Distributed Compression in Microphone Arrays", to appear in Distributed Source Coding: Theory, Algorithms, and Applications (P. L. Dragotti and M. Gastpar, eds.), Elsevier, 2009.

RoyV08b O. Roy and M. Vetterli, "Rate-Constrained Collaborative Noise Reduction for Wireless Hearing Aids", to appear in IEEE Transactions on Signal Processing, 2008.

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Full list available at `http://lcavwww.epfl.ch/~oroy`

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